Xtellcor_general User's Manual*
v4.0

Michael Cushing, William Vacca, John Rayner

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Contents

1 Introduction

`Xtellcor (General)` is a general version of the `xtellcor` routine that can be used on any near-infrared spectra. There are several limitations to this routine including 1) only a single spectrum can be manipulated at a time, and 2) the instrument profile is assumed to be a gaussian.

`Xtellcor` is the telluric correction program written by Bill Vacca and Mike Cushing for use with SpeX. This program works only if the standard star is an A0 V star since `xtellcor` uses a high-resolution model of Vega to remove the intrinsic stellar features. Users can find a description of the code in the paper by Vacca, Cushing, & Rayner (2003, PASP, 115, 389) and we would ask all users to reference this paper if they use `xtellcor`.

Three additional programs associated with `xtellcor` are `xtellcor_finish`, `xtellcor_basic` and `xtellcor_general`. `xtellcor_finish` allows the user to apply previously generated telluric correction spectra to data, `xtellcor_basic` allows the user to divide by a standard star (and optionally multiple by a Plank function) which can be useful for solar system observations, and `xtellcor_general` is a general version of the code for use with other instruments.

1.1 References

We ask that if a user uses one these routines, that they reference the following paper:

- **Telluric Correction:** Vacca, Cushing, & Rayner (2003, PASP, 115, 389)

2 Spextool Installation and Setup

Note: *Spextool requires IDL 7.0 or later and we assume that the user already has IDL running properly on its own.*

1. Spextool requires IDL 7.0 or later. We furthermore assume that the user has successfully installed IDL and can use it before he or she has installed Spextool.

   Note: *Simply starting up IDL is not necessarily an indication that IDL is installed properly. A good test is to attempt to launch the GUI* `xloadct`*. If IDL crashes, then IDL has not been properly installed.*

2. If the user is upgrading from a previous version of Spextool, please delete the previous version of Spextool (or move it out of your IDL path). Download the gzipped tar file from http://irtfweb.ifa.hawaii.edu/~spex/ and unpack it. For example, on a Unix-based system you would type `tar zxvf Spextool.tar.gz` on the command line. This will create a directory called Spextool, which is hereafter referred to as the `packagedirectory`, and a number of sub-directories.

3. The user must now include Spextool directory and all subdirectories in their IDL path. This can be accomplished in various ways.

   - If the user has a single IDL directory that is searched recursively for IDL libraries, then simply place the Spextool package in this directory. If the user stores other IDL libraries in the same directory but must load them into the IDL path on a case by case basis (due to various dependencies), then Spextool may be loaded at any point in the IDL path.
   - If this is the first time the user is installing an IDL package, we recommend creating a single directory, .e.g. `IDL`, into which the Spextool and other packages can be placed. Then the user must include this directory in their IDL path. This can be done in a number of ways, including adding the path to your `.idl_startup` file, or adding it to your IDL_PATH environment variable.

     For example, on a Unix-based machine using the C shell, edit the `.cshrc` file to include the line:

     ```
     setenv IDL_PATH +rootdir/IDL:$IDL_PATH
     ```

     if the IDL_PATH variable has already been defined in the file and

     ```
     setenv IDL_PATH +rootdir/IDL/:'<IDL_DEFAULT>'
     ```

if it has not. The + sign tells the system to recursively search the subdirectories in the Spextool package.

Note: *It is crucial that all the subdirectories in the Spextool package be added the the IDL path.*

4. Spextool requires two additional IDL libraries in order to operate properly:

   - **The Astronomy User's Library**: The main page is located at the following URL: http://idlastro.gsfc.nasa.gov/homepage.html. The user must install both the main library **and** the coyote routines required by the Astronomy User's Library (see below).
   - **The Markwardt MPFIT Package:** The main page is located at the following URL: http://www.physics.wisc.edu/ craigm/idl/idl.html.

   If the user has these libraries already installed on their system, then no further action is required and they can move on to the next step. If not, the user should download these packages and install them as described in step #2. The two astronomy libraries (some form of `astron.tar.gz` and `coyote_astron.tar.gz`) can be downloaded from this URL: http://idlastro.gsfc.nasa.gov/ftp/. The Last Modified date on the libraries should be no earlier than 14 Jun 2014. The MPFIT package can be downloaded from this URL: http://www.physics.wisc.edu/ craigm/idl/listing.html. The Last Modified date on the library should be no earlier than 14 Aug 2013. For the convenience of users who will only every use IDL for Spextool, we have included copies of these libraries in `Spextool/other/`.

5. *An incorrect path is one of the most common causes of problems encountered in attempting to run Spextool for the first time.* The user can start IDL and type `mc_testspextoolpath` at the IDL prompt to test whether he/she has set the paths correctly.

6. On a Unix-based system, pop-up menu lists can be made to respond to mouse scroll wheel input by modifying a set of resources associated with the X11 windows environment. Add the following to your `.Xdefaults` file:

```
*XmList.baseTranslations:  #augment <Btn5Down>:ListNextPage()\n
<Btn4Down>:ListPrevPage() \n

*XmScrollBar.baseTranslations:  #augment <Btn4Down>:
IncrementUpOrLeft(0) IncrementUpOrLeft(1)\n
<Btn5Down>:  IncrementDownOrRight(0) IncrementDownOrRight(1) \n
```

   and either restart your X enviroment or incorporate the changes by typing

```
> xrdb -merge $HOME/.Xdefaults
```

in a terminal. Carriage returns should only be placed after the "\n" characters. You can now use the scroll wheel on your mouse to move within popup text windows. Moving the wheel in any text window (e.g., help windows) or file selection window will now perform "page up/page down". Moving the wheel while over a text scroll bar will move one line at a time. Thanks to J.D. Smith for this tip!

Common Cursor Commands

Some of the GUIs have interactive plot windows and the following are the cursor commands that are common to all of these GUIs.

- a - Sets the **A**bsolute range to the current x and y range.

  This is very useful if the spectrum has a bad pixel as this x and y range is what will be used when the user clicks 'w' rather than the min/max of each range.

- c - **C**lear mouse mode. Use to clear a zoom or any selection mode.

- i - To zoom **I**n in whatever zoom mode the cursor is currently in.

- o - To zoom **O**ut in whatever zoom mode the cursor is currently in.

- w - To plot the **W**hole spectrum, i.e. the full range of the spectrum.

- x Enters the **x** zoom mode.

  Press and release left mouse button at lower x value and then at upper x value.

- y - Enters the **y** zoom mode.

  Press and release left mouse button at lower y value and then at upper y value.

- z - Enters the **Z**oom mode.

  Press and release the left mouse button in one corner of the zoom box and then move the cursor to the other corner and press and release the left mouse button.

3 Xtellcor_general: Telluric Correction and Flux Calibration

3.1 Cursor commands

The following cursor commands are used in various subroutines described below.

- e - to **e**stimate the scale factors in the `xscalelines` GUI.
- f - to **f**ix a region of the telluric spectrum in the `xscalelines` GUI.

  Press and release the left mouse button on the left and right side of the bad region. The bad region is replaced using the edge pixels to define a line. Type "u" to undo the edit.
- m - to **m**odify the boundaries of a selected continuum region in the `xconkern` GUI.
- n - Cursor enters **n**ormalization mode in the `xconkern` GUI.

  Select continuum regions to normalize the spectrum by clicking the left mouse button on the left and right sides of the region.
- s - to **s**elect a wavelength region in the `xconkern` and `xfindshift` GUIs.
- u - to **u**ndo a **f**ix in `xscaleines`.

3.2 Starting up and Loading the Data

1. Type `xtellcor_general` at the IDL prompt. This will bring up the `xtellcor (General)` GUI, which is divided into four sections corresponding to the steps to be carried out in performing the telluric correction.
2. In box #1, enter the fullpath of the standard star file in the **Std Spectra** field. This file should be a ASCII file with wavelength in the first column and "flux" in the second column. A third column with error values is optional. The suffix of the ASCII file must be either `.dat` or `.txt`. The file can contain commments as long as the line begins with a '#'.
3. Enter the B- and V-band magnitudes in the **Std Mag (B,V)** fields. If the magnitudes are unknown, the user can enter the same magnitude (any number) for B and V. In this case, the pseudo flux calibration will not be correct.
4. Enter the fullpath of the object spectra in the **Obj Spectra** field. The file must have the same format as the standard star file.
5. Choose the **wavelength units** (μm, nm, Å) for the input files from the pull-down menu.

6. Give the **FWHM** of the instrument profile. The units must be the same as that chosen for the wavelengths. The code currently assumes that the instrument profile is a Gaussian of the specified width.

7. The observed absorption lines in the A star spectrum may be intrinsically broadened by rotation. If the rotation velocity is larger than the corresponding spectral resolution of the observations, this broadening will be noticeable and the IP convolution procedure (see below) may not be able to generate an accurate stellar template spectrum from the Vega model. The resulting telluric correction spectrum may contain spurious artifacts and produce unsatisfactory results. To compensate for this, xtellcor allows the user to input a value of the rotation velocity (in km s^{-1}) of the standard star, which is then used to broaden the Vega model. The rotation velocities of A stars can often be found in the literature. The rotation-broadened Vega spectrum is then used with the IP to generate a template spectrum and a telluric correction spectrum.

8. Click the **Load Spectra** button to load the spectra into memory.

3.3 Constructing the Telluric Spectrum

9. The user can now make adjustments to account for the fact that the observed A0 V star may not have the same strengths of the Hydrogen lines as in the Vega model spectrum. Click on the **Scale Lines** in Box 2 and the `xscalelines` panel will appear.

   In the bottom window of the panel is the estimate of the telluric spectrum (in white) and the atmospheric transmission at the resolving power of the data (in yellow). The telluric spectrum, or the result of applying this telluric to the object spectrum, can be viewed by selecting either the **Telluric** or **Object** button in the middle of the GUI. The positions of the Hydrogen lines present in A0 V stars are labeled and marked in green.

   Ideally, the telluric spectrum should look similar to the typical atmospheric absorption spectrum times the instrument throughput (which is a smoothly varying function). However, because the Equivalent Widths of the H lines in the observed star do not necessarily match those in the model spectrum of Vega, broad "emission" or "absorption" features may appear in the telluric spectrum at the wavelengths of the H lines. Xscalelines provides a method of scaling the model equivalent widths in order to remove these features from the telluric spectrum.

   In the upper panel is a plot of the initial scale factors used by the program to scale the H line Equivalent Widths in the model spectrum. If the user constructed the kernel with the Deconvolution Method, all the scales will be set to the ratio of the equivalent width in the observed spectrum to the equivalent width in the model spectrum. If the user constructed the kernel with the IP Method, all scales will be set to unity.

10. The goal of this step is to remove the stellar H lines from the telluric spectrum and generate a telluric correction spectrum that contains only those features due to atmospheric absorption.

The typical telluric spectrum shown in yellow should give the user an idea of where the true atmospheric features are, what their approximate relative strengths should be after removal of the stellar H lines, and how much the H lines in the (white) telluric spectrum should be scaled. To scale the strengths of the H lines, the user can zoom in on a region around any stellar H line in the bottom panel with the 'z' command. If the line is fairly isolated and has continuum regions on either side of it, the user can type 'e' (for **e**stimate) and click the left-most mouse button twice, once on each side of the feature in the continuum regions. `xscalelines` will automatically attempt to compute the best scale factor for that particular line based on a fit of a background+gaussian profile to the region in the telluric spectrum selected with the 'e' command (we do not recommend use 'e' on the H lines in LowRes15 spectra, see below). The scale factors can also be adjusted by hand by clicking on the green points in the upper window with the left-most mouse button, holding the button down, and dragging the point up or down.

If the user finds that s/he is unable to satisfactorily remove the the stellar H line from the telluric correction spectrum, s/he has the option of linearly interpolating over any remaining residual features. This option can also be used if the star used as a telluric standard is found to have emission - rather than absorption - at some of the H transitions. Type 'f' (for **f**ix) and then click the left mouse button on the left and then right side of the residual feature. The residual feature will be interpolated over using the flux values at the wavelengths chosen by the user. To undo the interpolation, type 'u' (for **u**ndo).

Note: *The interpolation feature should be used with caution since any atmospheric features present will also be removed from the telluric correction spectrum. We recommend restricting the use of this option to only those regions and features where the typical atmospheric spectrum is seen to be very smooth (e.g. in order 8 of the SXD mode).*

Whenever the scale factors are adjusted (either by using the 'e' or 'f' commands or by dragging them by the user by hand), `xscalelines` will fit a spline through all the scale factors at each H line and use the new array of scale factors to recompute a new telluric spectrum. The telluric-corrected object spectrum can be examined at any stage by selecting the "Object" button at the top of the lower window. This will show the user what the effects of changing the scale factors are on the object spectrum. However, we do not recommend that users base their scale factor adjustments on the results seen in the Object spectrum! The scale factors should be adjusted based on the generation of a telluric spectrum that approximates the typical atmospheric curve.

11. Examine the telluric spectrum in each order (by selecting the order from the "Order" pull-down menu in the middle of the Xscalelines panel) and correct as many features as necessary using the method described above. Typically, orders 7 and 8 in the SXD mode require the most corrections, and often they require the interpolation option described above.

    Note that for some features it may not be possible to remove the residuals completely. This is particularly the case when using the IP mode. In some cases it may be necessary to shift

the Vega model spectrum relative to the observed spectrum in order to decrease the size of the residuals. (A relative velocity offset is computed in the "Deconvolution" method, but not when the "IP" method is used.) The user can enter a relative velocity in the "Vshift" field at the top of the Xscalelines window. The Vega model used to construct the telluric correction spectrum is then shifted and a new telluric correction spectrum is generated. Note that the velocity shift is applied to all orders simultaneously. It is not possible to apply different velocity shifts to different orders.

12. When the user is satisfied with the telluric spectrum in each order, s/he should click on the **Accept** button at the bottom of the `xscalelines` GUI.

13. When all orders have been inspected and the line scaling has been finished, the user can select the units desired for the output telluric-corrected object spectrum from the **Units** pull-down menu. Then click on the **Construct Telluric Spectrum** button. The program will then construct the telluric spectrum for each order by dividing the observed A0V standard star spectrum by the convolved and scaled Vega model whose H line EWs have been adjusted as described in steps 18-19.

3.4 Determining Residual Wavelength Shifts

We often find there are slight wavelength shifts between the A0 V star used to construct the telluric spectrum and the object to be corrected. These shifts need to be removed in order to avoid introducing spurious noise and artifacts when dividing the object spectrum by the telluric spectrum.

Note: *This step is optional and can be skipped if the user so desires.*

14. To estimate the wavelength shift for a given spectrum and correct for it, choose an Aperture and an Order from the pull-down menus in Box 3. Click on the **Get Shift** button and the `xfindshift` GUI will appear. The object spectrum (white) and the telluric spectrum (green) are both plotted in the upper window along with the atmospheric transmission at the resolving power of the data (yellow). The result of dividing one by the other is shown in the bottom window.

15. Select a region in the top window containing a reasonably strong atmospheric features in both spectra (and preferably one not containing strong absorption or emission features in the object spectrum). This is done by typing "s" (for **s**elect) and click with the left-most mouse button on either side of the features. Then click on the **Auto Find** button in the upper left of the window. `xfindshift` will shift the telluric spectrum by fractions of a pixel and search for the best value, corresponding to a minimum in the RMS computed from the telluric corrected spectrum in the selected region. Alternatively, if the user desires a specific shift value (perhaps as the result of determining the shift from another order), s/he can enter the

value directly in the **Shift** field and hitting return. Similarly, wavelength shifts can be reset to zero by entering zero in the **Shift** field and hitting return. The user can determine the shift obtained from a different wavelength region by typing "s" and selecting a new wavelength region. When the user is satisfied with the shift found by `xfindshift`, s/he should click on the **Accept** button at the bottom of the window.

16. The user should determine shift values for each order/aperture independently by selecting a new order/aperture in Box 4 and repeating the previous step.

3.5 Write the File to Disk

17. Give the root of the output file name in the **File Name** field in Box 4 (the .dat suffix will be automatically appended to the root). The user can also choose to output the telluric correction spectrum as well as the modified Vega model spectrum (shifted to the radial velocity, scaled to the optical mag of the input standard star, convolved with the kernel, and multiplied by the equivalent width scale factor array). Click on the **Write File** button to generate the output files. The spectrum will be displayed in the `xzoomplot` GUI. If the user chose to output the telluric correction spectrum or the modified Vega spectrum, they will be written to disk with the file names `root_tellspec.dat` and `root_modvega.dat`. An an example of the ASCII file output is given below:

```
#
# Generated by xtellcor (General), Wed Dec 31 15:45:46 2014
#
# A0VBmag = 7.00000  - B-band magnitude of A0 V star
# A0VVmag = 7.00000  - V-band magnitude of A0 V star
# FWHM = 0.0100000 - FWHM of gaussian kernel in XUNITS
# Vrot = 0.00000 - Rotation speed of standard star in km s-1
# VEGADV = 0.00000 - Vega velocity shift in km s-1
# XUNITS = um - Wavelength units
# YUNITS = ergs s-1 cm-2 A-1 - Intensity units
#
0.668454   -4.84107e-17    3.15197e-17
0.669697   -5.01489e-17    1.46637e-17
0.670945   -1.48168e-17    1.72300e-17
0.672197   -8.40323e-18    1.91562e-17
0.673455   -1.99023e-17    3.71247e-17
```